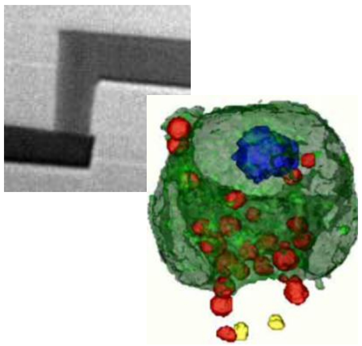
Source radiance requirements for high-resolution imaging and interference techniques

Larissa Juschkin

RWTH Aachen University

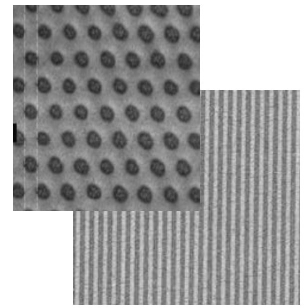
Applications summary

XUV: short wavelength and strong light matter interaction	→	lateral & in-depth (3d) nm resolutions with element sensitivity and high throughput



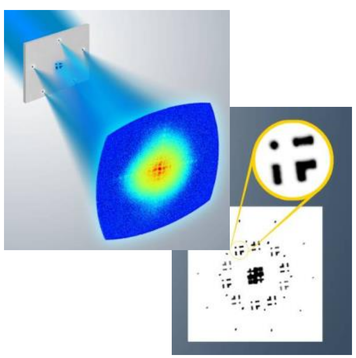
Microscopy

- 3d imaging (cells, electronics)
- “no” sample preparation
- several µm penetration depths
- magnetic (spin) contrast with polarized light



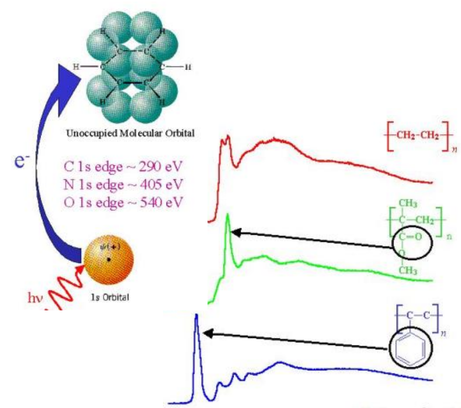
Patterning

- high density arrays
- large exposition areas
- access to < 10 nm scale
- negligible proximity effect
- independent on substrate



Scatter/diffractometry

- nano-roughness
- nano-structures arrays
- nano-defect inspection
- lens less imaging with coherent light



Spectroscopies

- element selectivity
- chemical bonding (NEXAFS)
- small penetration depths of radiation (<100 nm)
- large grazing incidence angle

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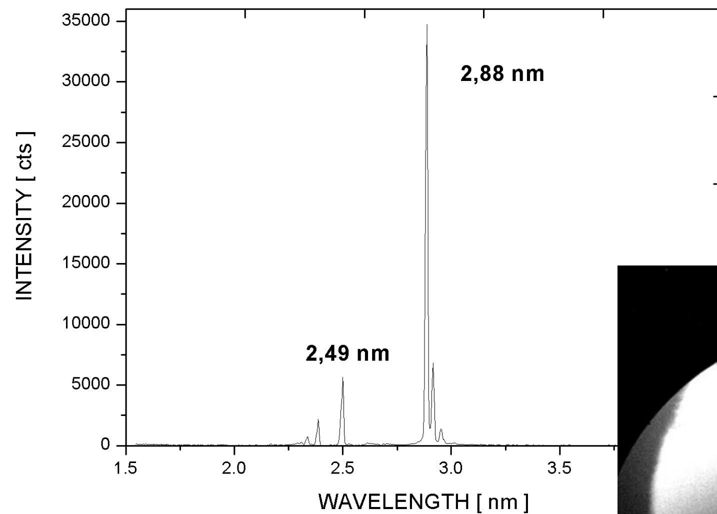
EUV and soft x-ray microscopy: element-sensitive contrast and high spatial resolution (down to ~10 nm)

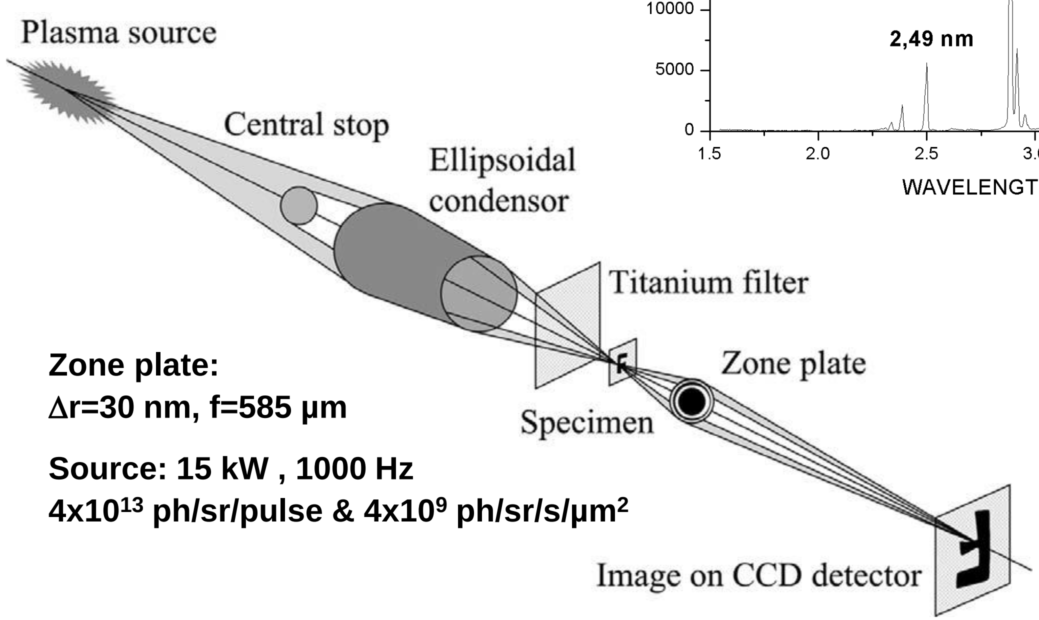
Discharge Source

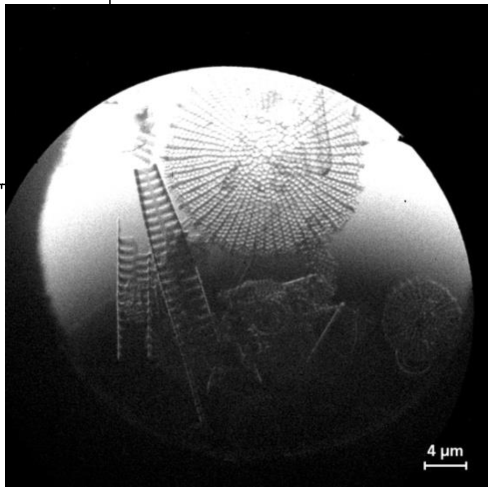
Working gas: Nitrogen

28 W/sr/cm^2 @ single line at 2.88 nm



Diatom in bright- and dark field illumination mode (due to special illumination of the zone plate)





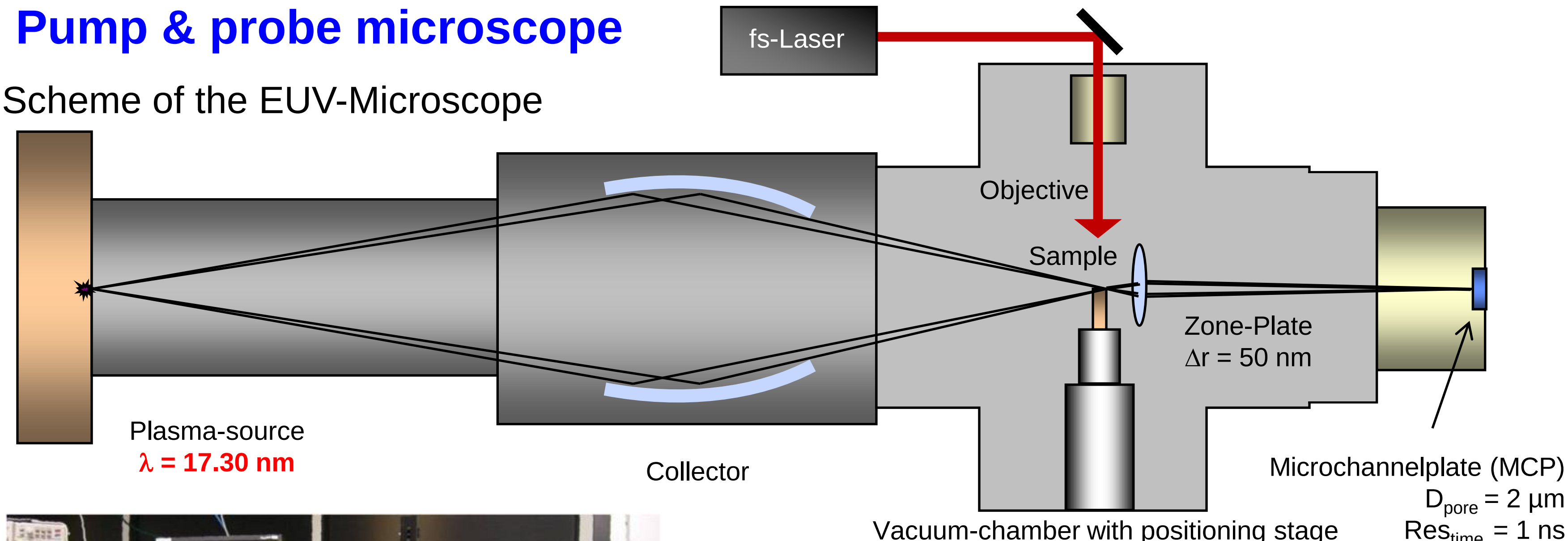
Zone plate:
Δr=30 nm, f=585 µm

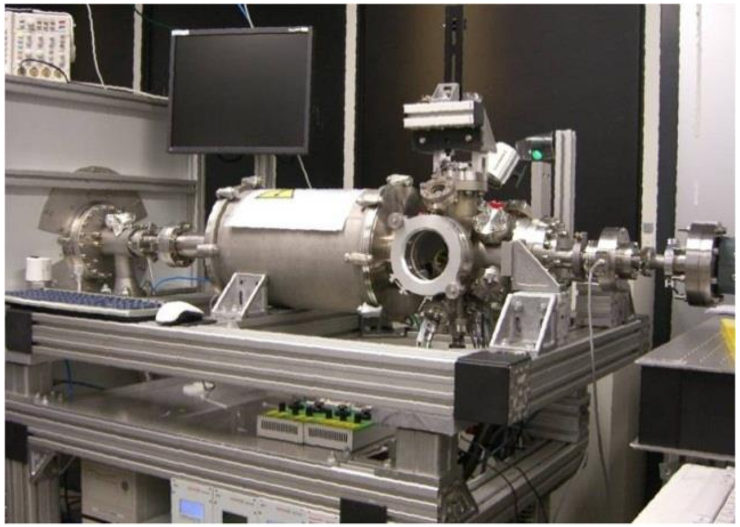
Source: 15 kW , 1000 Hz
4x10^{13} ph/sr/pulse & 4x10^9 ph/sr/s/µm^2

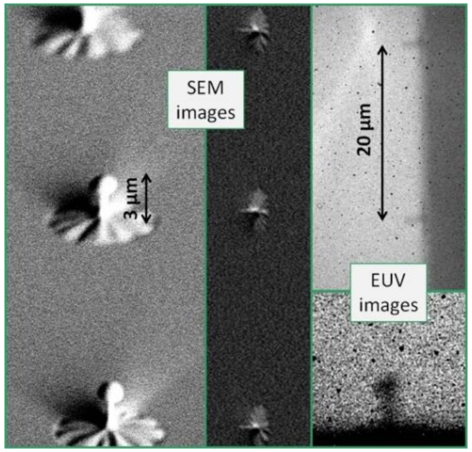
Courtesy of K. Bergmann, M. Benk, FhG ILT, and Th. Wilhein, D. Schäfer, FH Remagen

Pump & probe microscope

Scheme of the EUV-Microscope







Nano-jets from Au thin film induced by a femtosecond laser pulse

M = 375
RES = 75 nm

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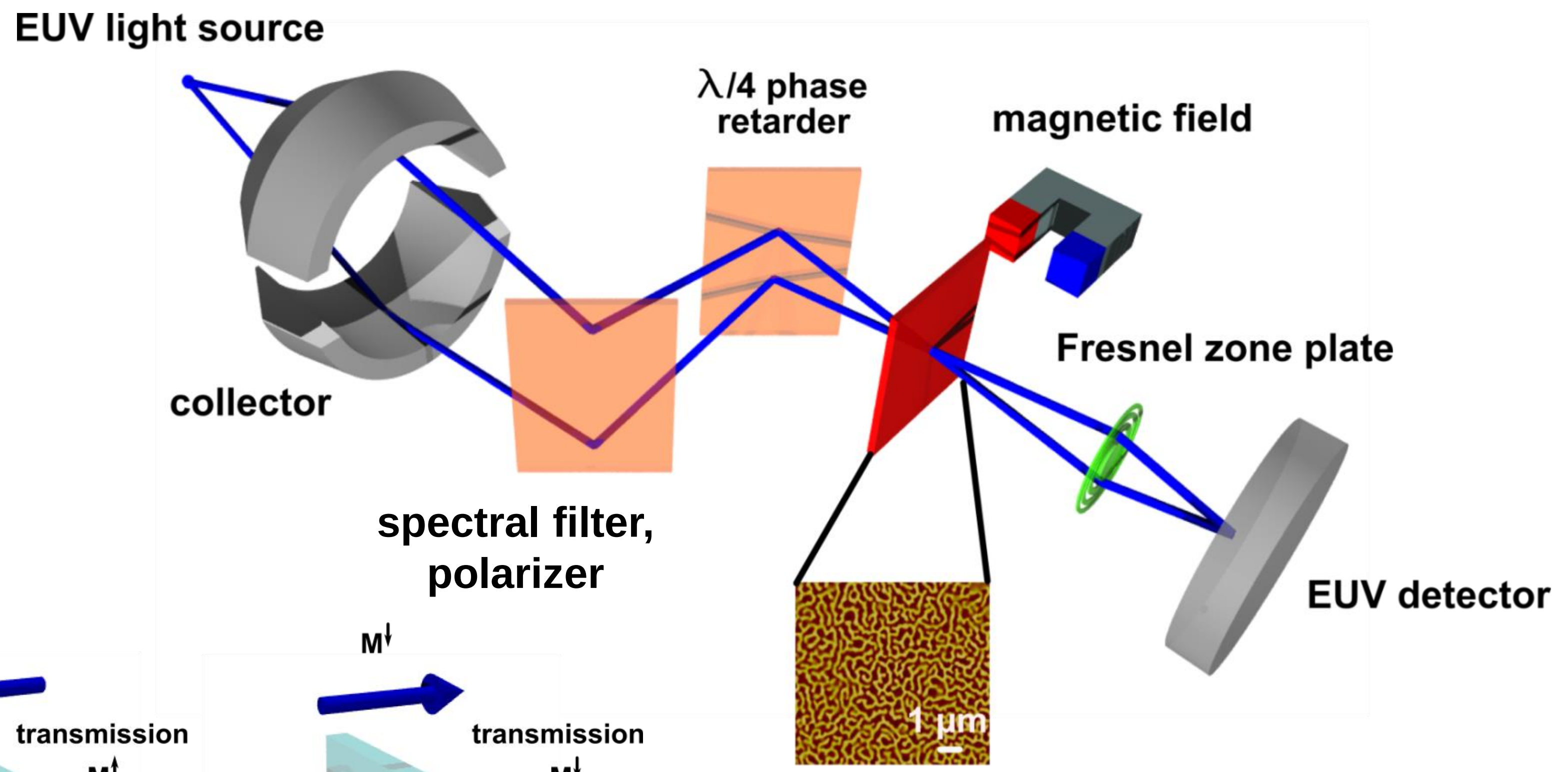
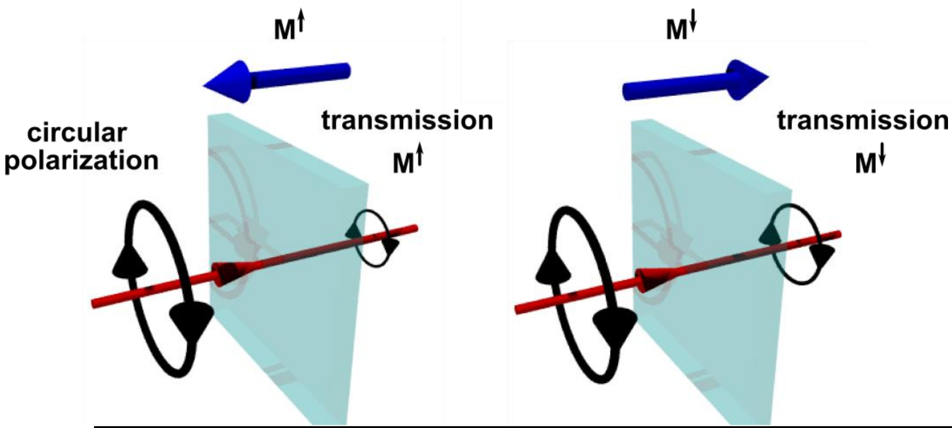
Magneto-optical microscope



X-ray magnetic circular dichroism (XMCD)



Effect ~100x larger than in visible range!

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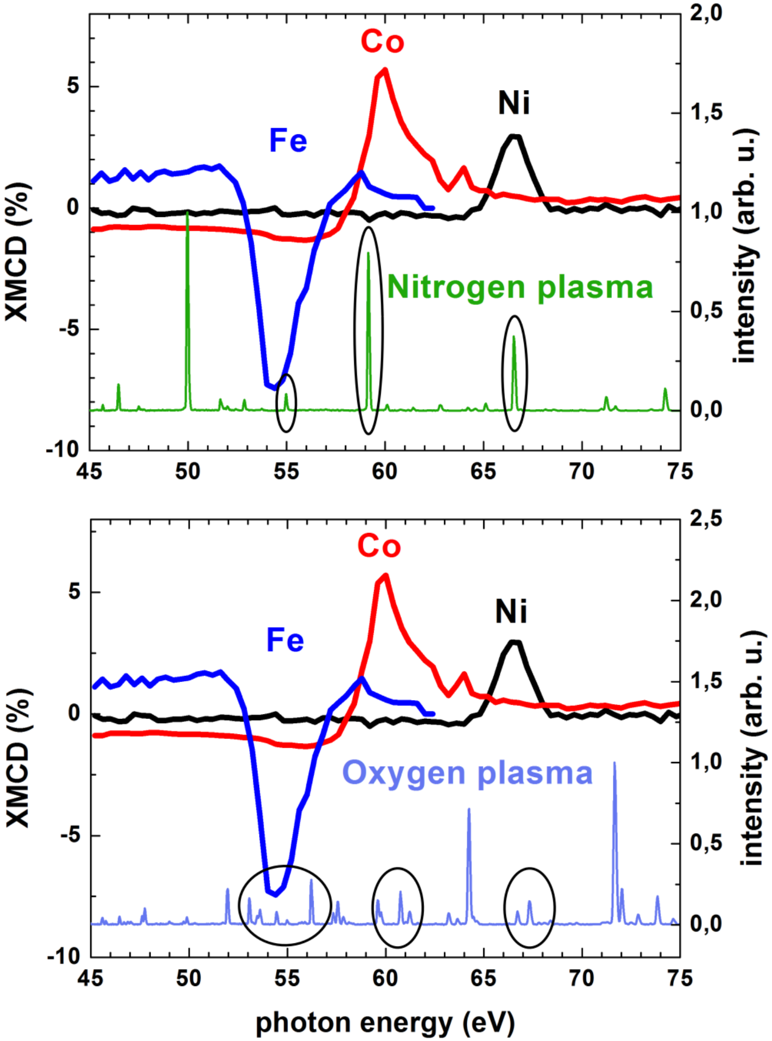
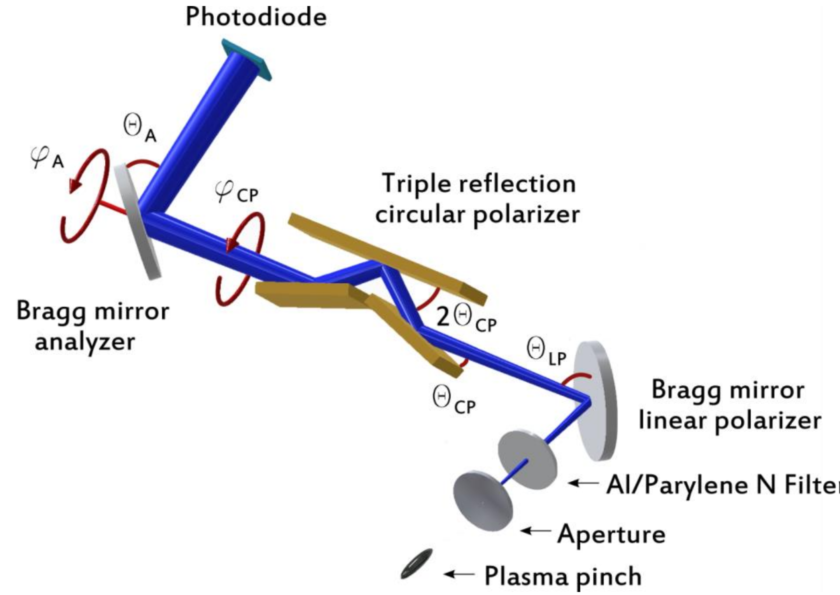
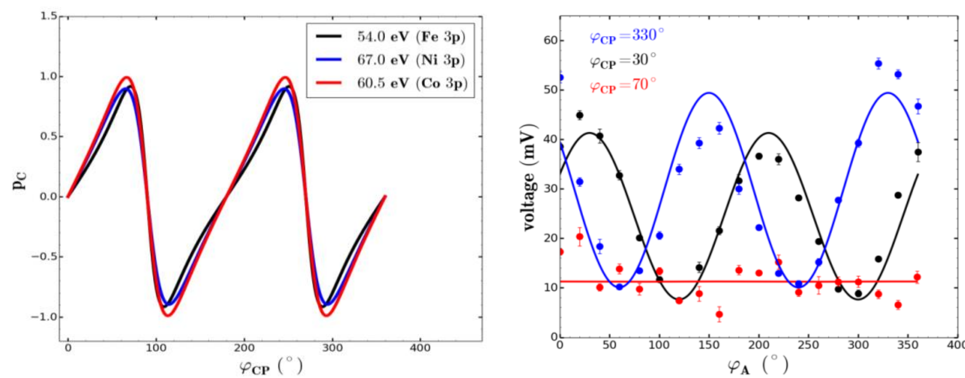
XMCD-contrast at 3p edges of Fe, Co and Ni







D. Wilson, D. Rudolf, et al., Review of Scientific Instruments 85, 103110 (2014)

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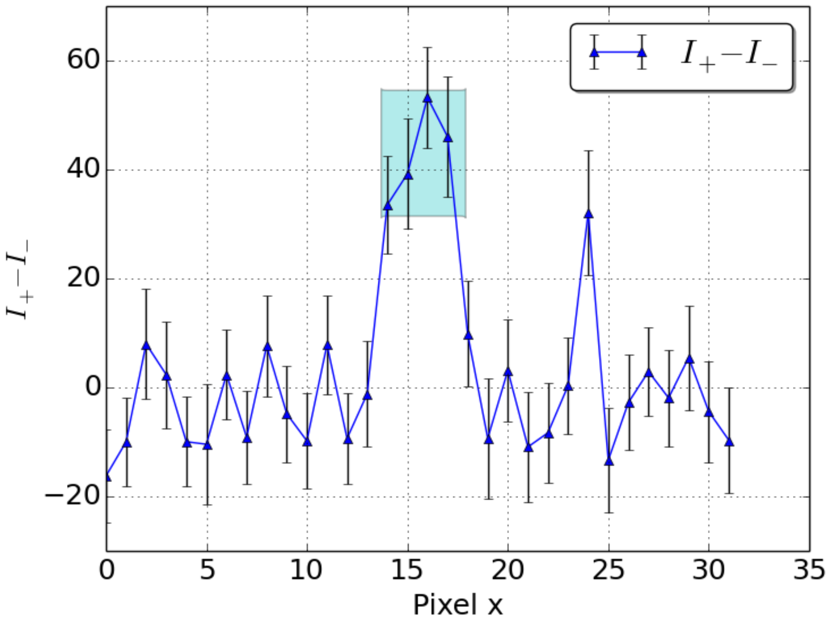
XMCD at Co 3p absorption edge

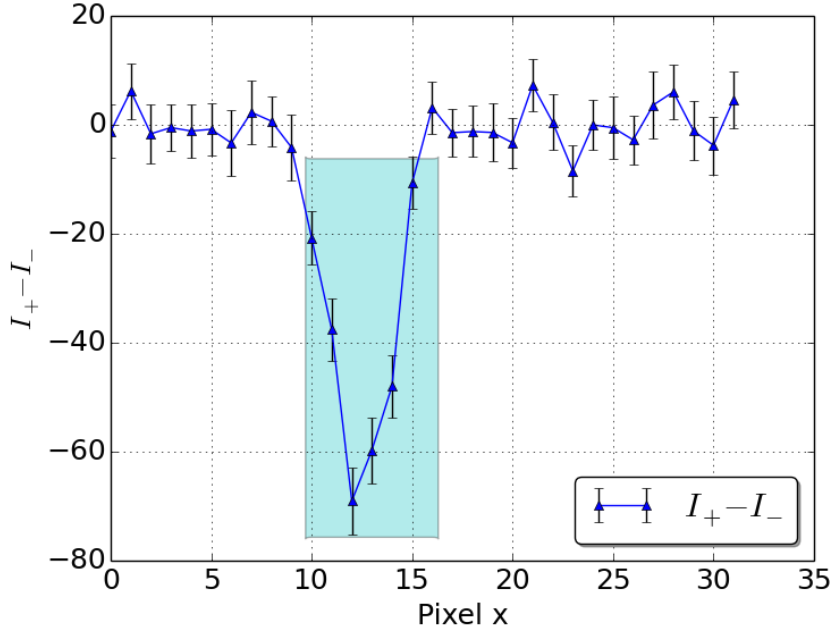
Sample: [Co (0.8 nm) / Pt (1.4 nm)]$_{16x}$

Positive helicity



$$A = \frac{T_+ - T_-}{T_+ + T_-} = (2.7 \pm 0.1)\%$$

Negative helicity



$$A = \frac{T_+ - T_-}{T_+ + T_-} = (-2.8 \pm 0.1)\%$$

D. Wilson, D. Rudolf, et al., Review of Scientific Instruments 85, 103110 (2014)

Photon detections: required flux based on contrast

Contrast:

$$C = \frac{\text{signal difference}}{\text{background}} = \frac{n_{ph\_f} - n_{ph\_b}}{n_{ph\_b}}$$

Sensitivity index:

$$d' = \frac{\text{separation}}{\text{spread}} = \frac{n_{ph\_f} - n_{ph\_b}}{\sqrt{n_{ph\_b}}}$$

d′ of at least 5 is needed for 100% certainty in distinguishing image features

"Signal Detection Theory" or A. Rose, "Television pickup tubes and the problem of vision", Advances in Electronics **1**, 131-166 (1948)

Quasi-ideal detector (signal noise dominating):

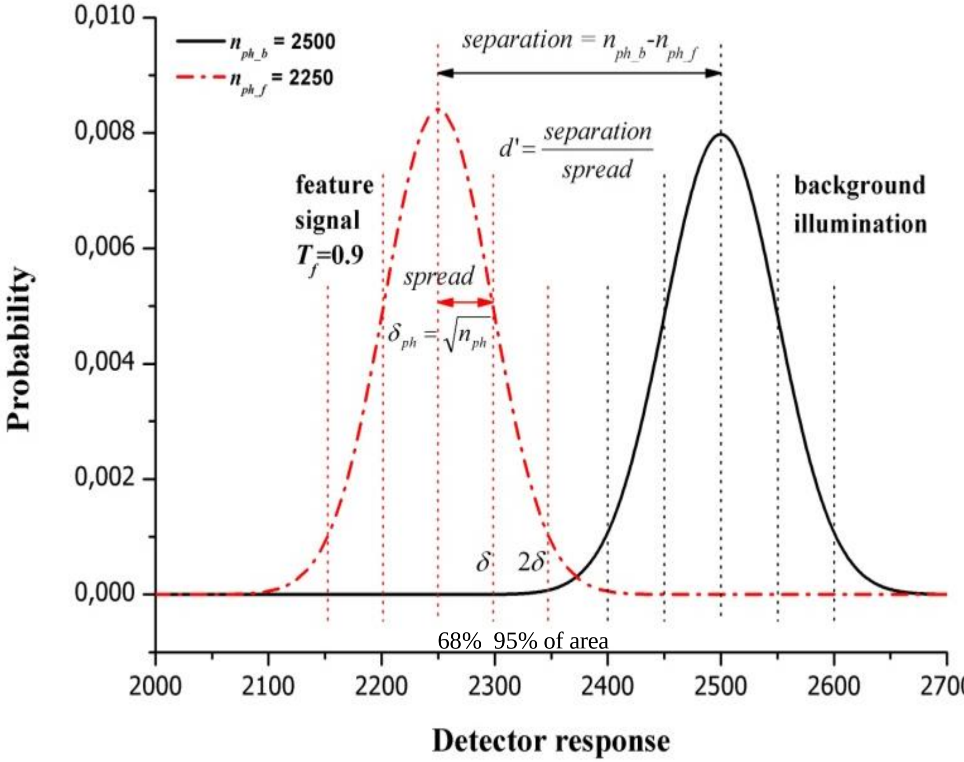
$$d'_{\text{det}} = \sqrt{QE} \cdot d'$$

Required number of photons:

$$\boxed{n_{ph\_b} \geq \frac{25}{QE \cdot C^2}}$$

photon detections → Poisson statistics

Photon noise: $\delta_{ph} = \sqrt{n_{ph}}$



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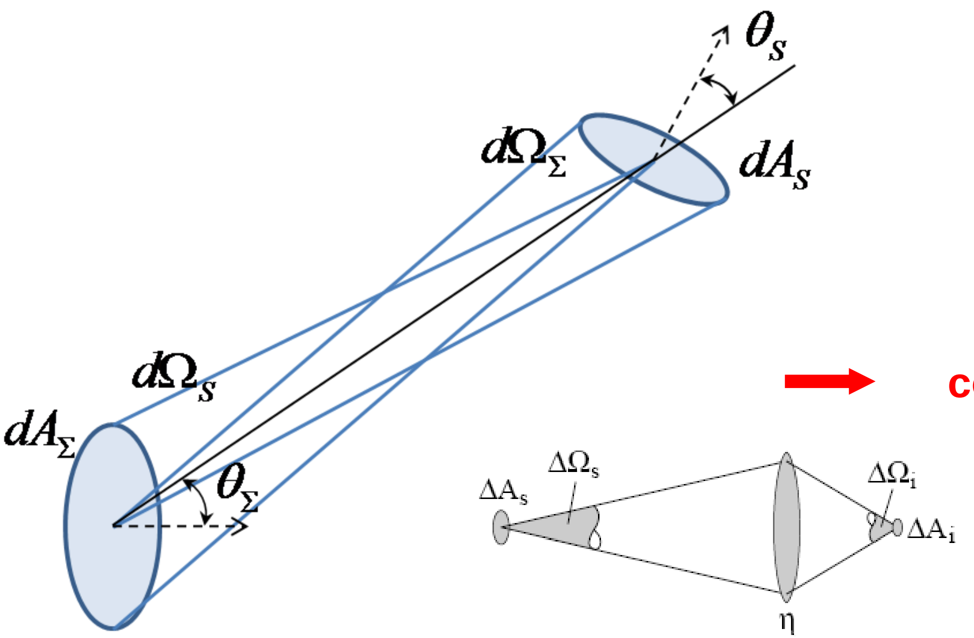
Source radiance and etendue

Spectral radiance: radiation energy (photons) per time interval, wavelength, solid angle and area

not increasing

$$\text{Radiance} = \frac{\text{photon flux}}{\text{etendue}} \qquad L = \frac{d^2\Phi}{dA \cdot \cos\theta \cdot d\Omega} = n^2 \cdot \frac{d^2\Phi}{d^2 G}$$

not increasing *not decreasing*



Etendue

$$G = \int_A \int_\Omega dA \cos\theta \cdot d\Omega = \pi \cdot NA^2 \cdot A$$

***NA* – numerical aperture**
***A* – field of view area**

constant in optical system (at best)

$$\Delta A_s \cdot \Delta\Omega_s = \Delta A_i \cdot \Delta\Omega_i \,;\; \eta = 100\%$$

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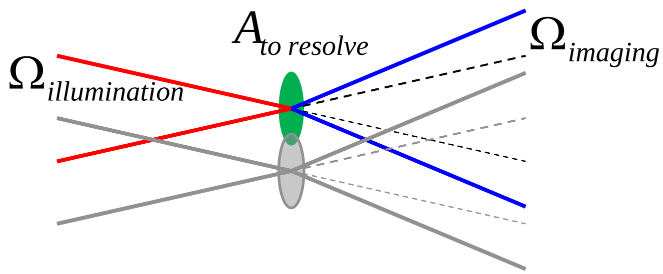
Requirements on source radiance

At sample:

$$n_{ph\_b},\quad t_{exposure},\quad \Omega_{illumination},\quad A_{to\ resolve} \quad \Rightarrow \quad L_{sample} = \frac{n_{ph\_b}\cdot E_{ph}}{t_{exposure}\cdot\Omega_{illumination}\cdot A_{to\ resolve}}$$



Transmission of the system: T_{system}

$$\Rightarrow \quad L_{source} = \frac{n_{ph\_b}\cdot E_{ph}}{T_{system}\cdot t_{exposure}\cdot\Omega_{illumination}\cdot A_{to\ resolve}}$$

$$\boxed{L = \frac{25\cdot hc/\lambda}{QE\cdot C^2\cdot T_{system}\cdot t_{exposure}\cdot\Omega_{illumination}\cdot A_{to\ resolve}}}$$

Bright field imaging: $NA_{im}=NA_{il}$

wavelength	2.88	13.5	nm
contrast	-0.1	-0.2	
T system	1	2	%
exposure	1	0.1	s
radiance	4	0.05	W/mm²/sr

Resolution matched imaging:

$$A_{to\ resolve} \cong \left(\frac{\lambda}{2\cdot NA_{imaging}}\right)^2$$

$$\Omega_{illumination} = \pi\cdot NA_{ill}^2 \Rightarrow L \cong \left(\frac{NA_{im}}{NA_{ill}}\right)^2 \frac{25\cdot hc}{QE\cdot C^2\cdot T_{sys}\cdot t_{exp}\cdot\lambda^3} \cong 5\cdot 10^{-3}\,\frac{NA_{im}^2/NA_{ill}^2}{QE\cdot C^2\cdot T_{sys}\cdot t_{exp\,[s]}\cdot\lambda^3{}_{[nm]}}\,\frac{W}{mm^2\cdot sr}$$

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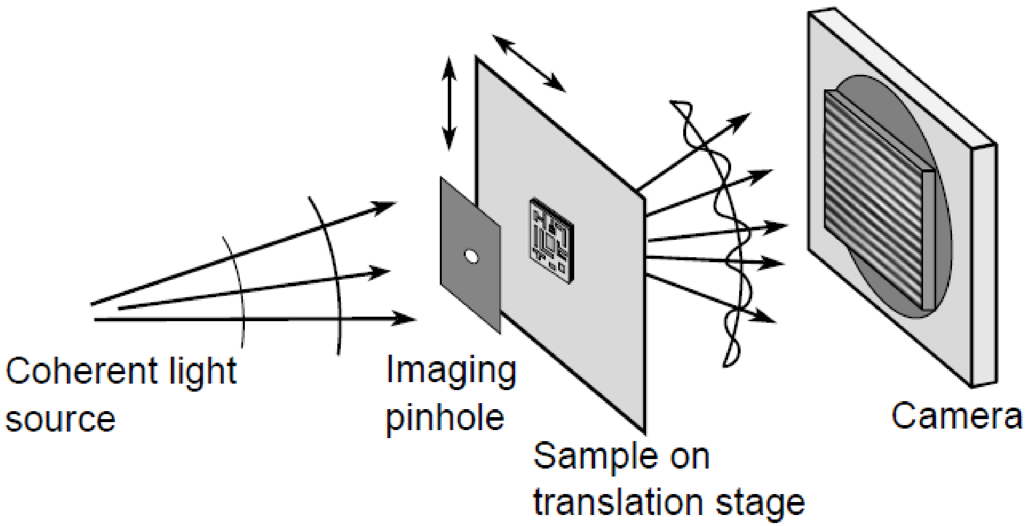
Laboratory-scale lens-less EUV imaging

Gains compared to standard lens-based microscopy

- **Not limited by quality of optics**
- **More compact setup, easier alignment**
- **Better use of incidence light => lower dose**
- **Reconstruction of phase shift and attenuation**

particularly suited for imaging with short wavelength radiation



XUV: short wavelength and strong light matter interaction

lateral & in-depth (3d) nm resolutions with element sensitivity and high throughput

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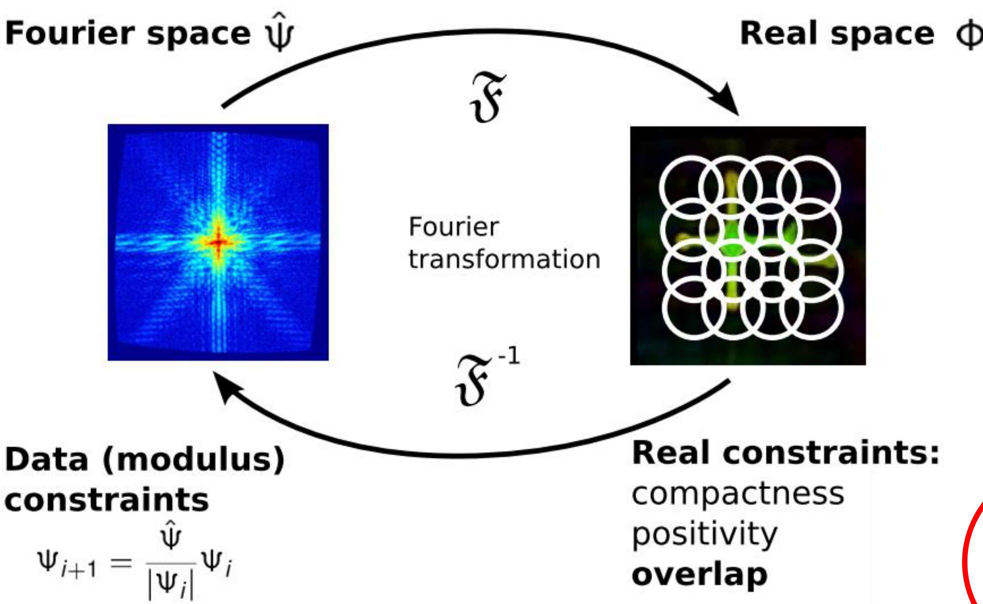
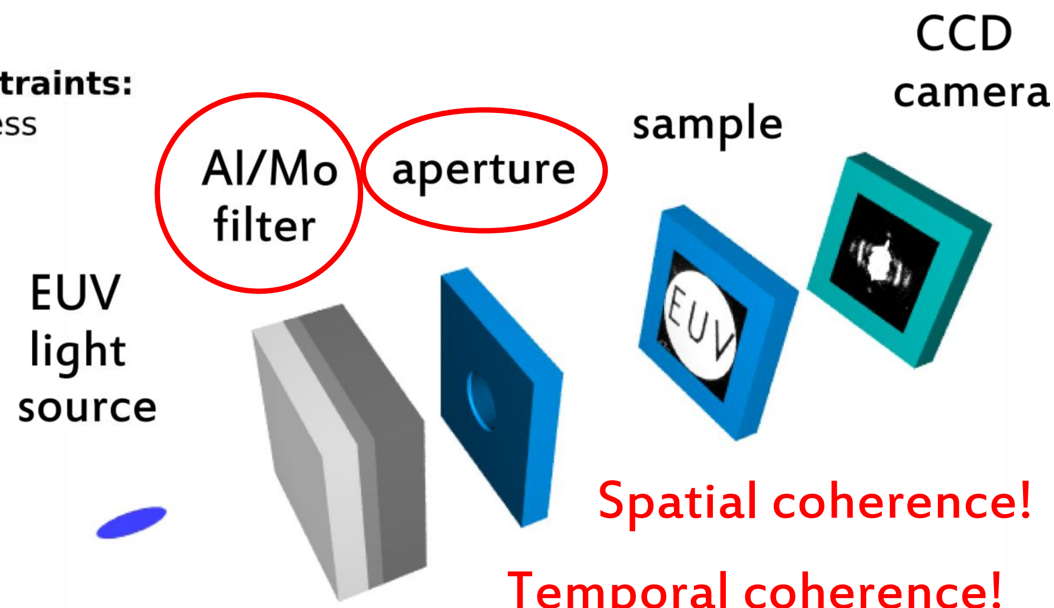
Basic principle for coherent imaging & experimental setup





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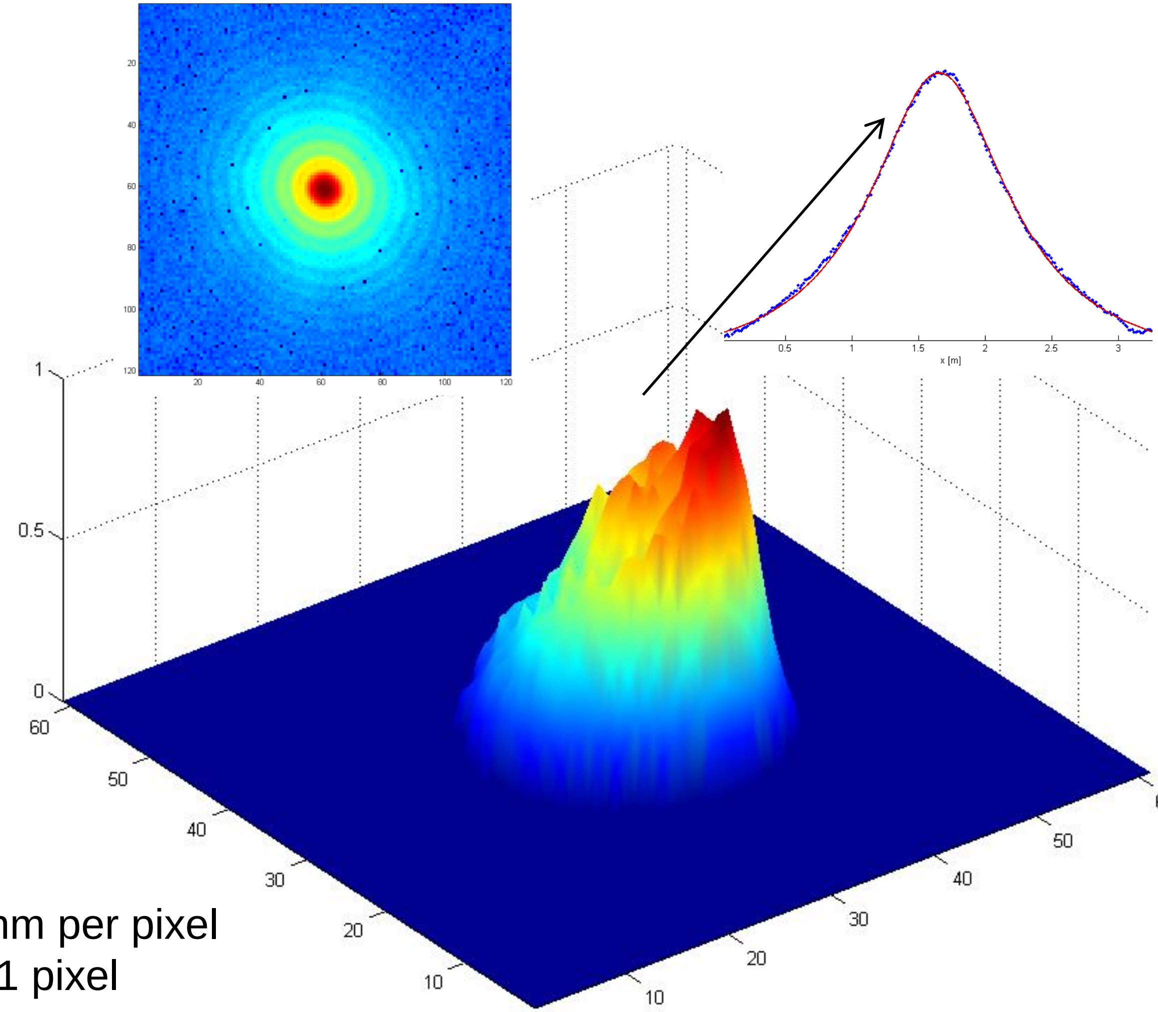
Reconstruction procedure and result: illumination wave front

1. Background subtraction
2. Hot pixel detection
3. Data binning (5x5)
 -> oversampling ratio reduction
 -> dynamic / SNR enhancement
(4. Symmetrizing)

5. Applying OSS algorithm (HIO + filtering outside of support) ->128 independent runs
6. Averaging of the top 5 images with lowest error (R_{factor}=12.8%)
7. Size determination from experimental distances: pinhole diameter: 11.2 µm



488 nm per pixel
61x61 pixel

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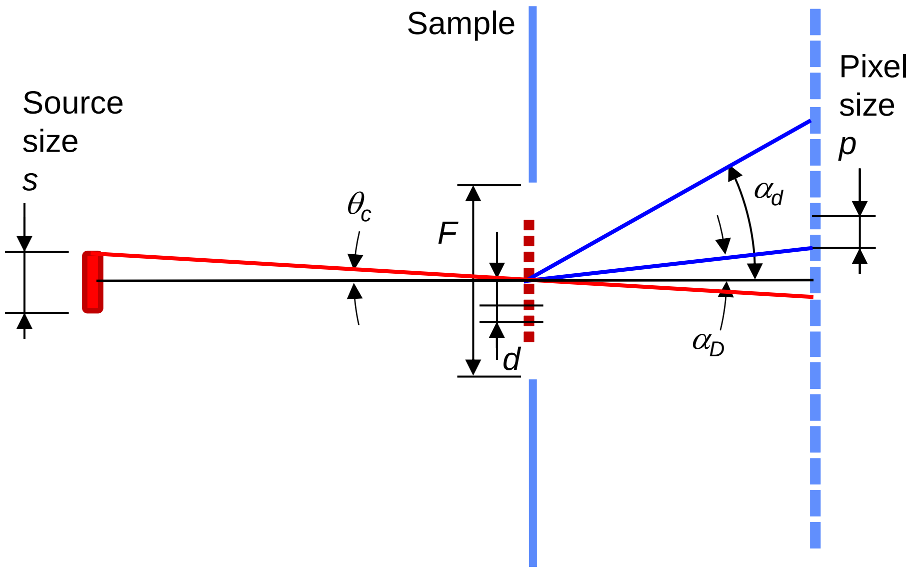
Coherence and radiance requirements for lens-less imaging



Different spatial frequences *1/d* are present at sample

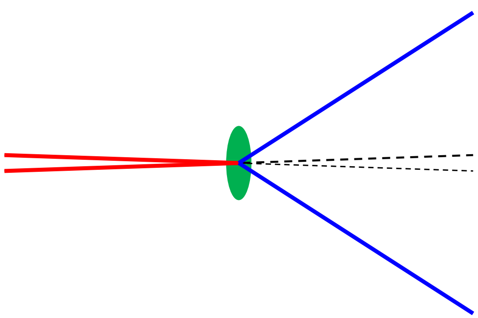
Diffraction angle $\sin\alpha_d = \lambda / d$

Oversampling *O > 2* is required for reconstruction

Resolution is determined by detector numerical aperture

Field size and oversampling determine minimum pixel numerical aperture

Number of pixels in image is determined by bandwidth: $N_{pixel} = \frac{\lambda}{\Delta\lambda} \cdot \frac{1}{O}$



$$\frac{NA_{imaging}}{NA_{illumination}} = O \cdot N_{pixel} \Rightarrow L = \frac{O^2 \cdot N_{pixel}^2 \cdot 25 \cdot hc}{QE \cdot C^2 \cdot T_{sys} \cdot t_{exp} \cdot \lambda^3}$$

phase and amplitude

better compared to lens-based imaging

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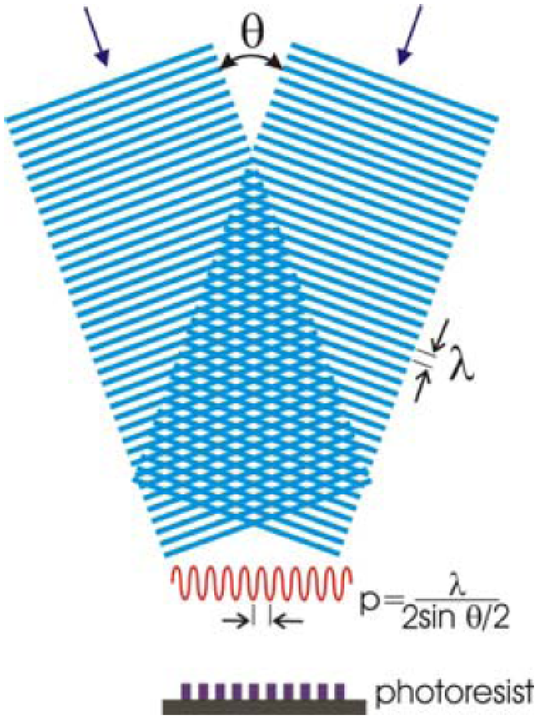
Interference lithography



- **Large-area periodic structures**
- **Large depth of focus**
- **Requires a coherent light**
- **Low cost – no complicated and expensive optics**
- **Ultimate resolution (half-pitch) for the wavelength ~λ/4**

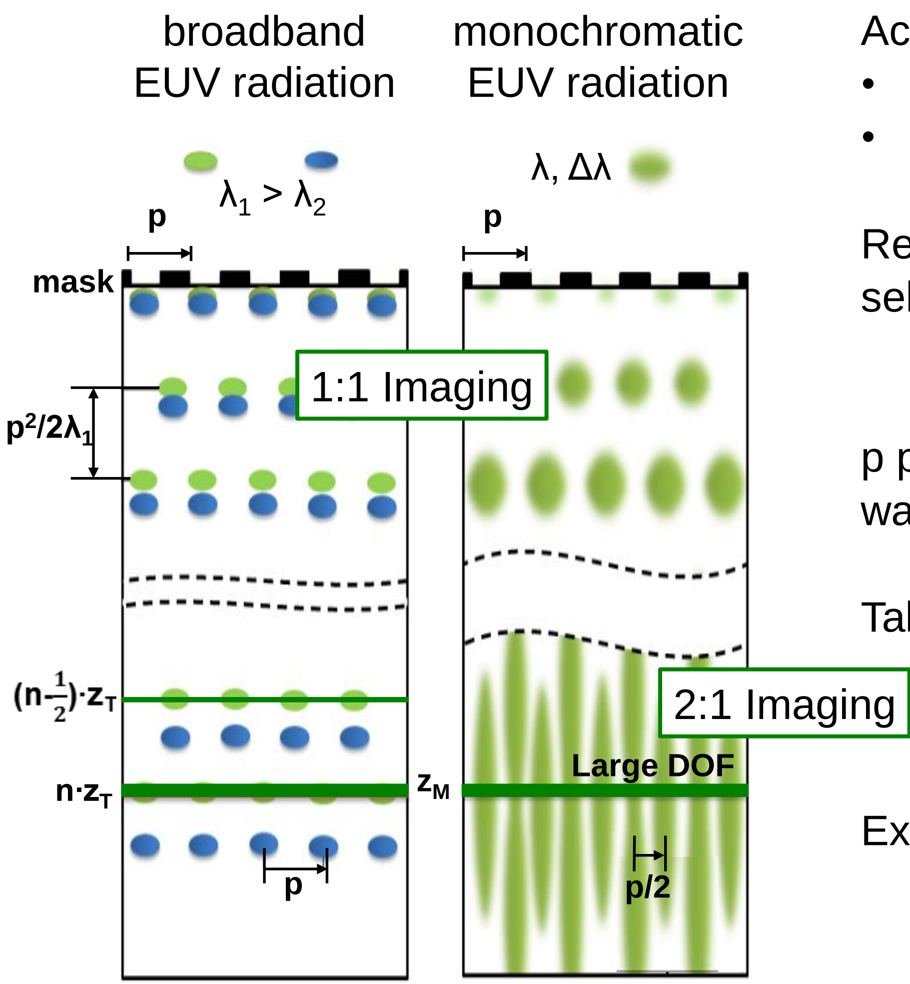
EUV: λ = 11 nm ➡ feature size: ~3 nm

EUV-IL: high resolution, scalable throughput, simple optical system, negligible proximity effect, no charging effects

Applications:

- **templates for guided self-assembly**
- **nano-optics, meta-materials**
- **ultra high density patterned magnetic media**
- **quantum dot 2D and 3D arrays, nanowire arrays**

Talbot self-imaging, 2:1 pattern demagnification



Achromatic Talbot self-imaging:

- Demagnification of pattern by up to a factor of 2
- Large depth of field

Required spatial coherence for achromatic Talbot self-imaging:

$$l_{coh}=4p\lambda/\Delta\lambda$$

p period for l/s or pinhole grating, λ illumination wavelength, $\Delta\lambda$ bandwidth of radiation

Talbot distance:

monochromatic: $n\cdot Z_T=2p^2/\lambda$
achromatic: $Z_M=2p^2/\Delta\lambda$

Example: n=1, p=100 nm, λ=10.9 nm, $\Delta\lambda/\lambda$=3.2%
monochromatic: Z_T=1.83 µm
achromatic: Z_M=57.33 µm

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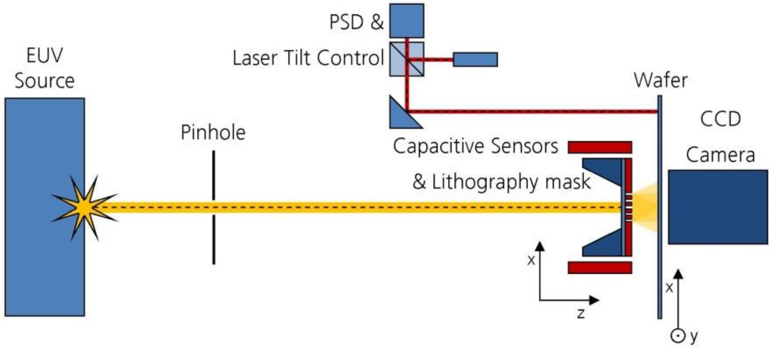
EUV laboratory exposure tool – technical specifications



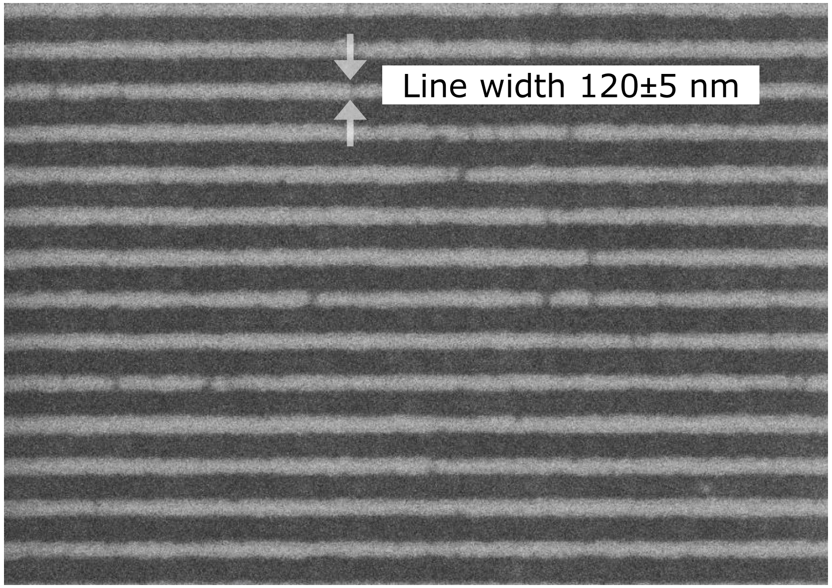
S. Brose, S. Danylyuk, L. Juschkin, D. Grützmacher *et al*, Thin Solid Films 520, 5080 (2012)

- Cleanroom class 100 (ISO 3) environment
- High power EUV discharge produced plasma source:
  - → Optimized emission spectrum with a peak wavelength at λ = 10.9 nm and a spectral bandwidth of 3.2%
  - → Up to 100 W/(mm^{2}sr) radiance at 10.9 nm
- Illumination schemes: proximity printing and Talbot interference lithography
- Accepts up to 100 mm wafer
- Max. exposable area: 65 x 65 mm^2
- Single field: 2 x 2 mm^2
- EUV sensitive CCD camera
- High precision positioners on all axes (encoder resolution < 10 nm)
- Dose monitor for λ = 13.5 nm

Exposure results EUV-LET

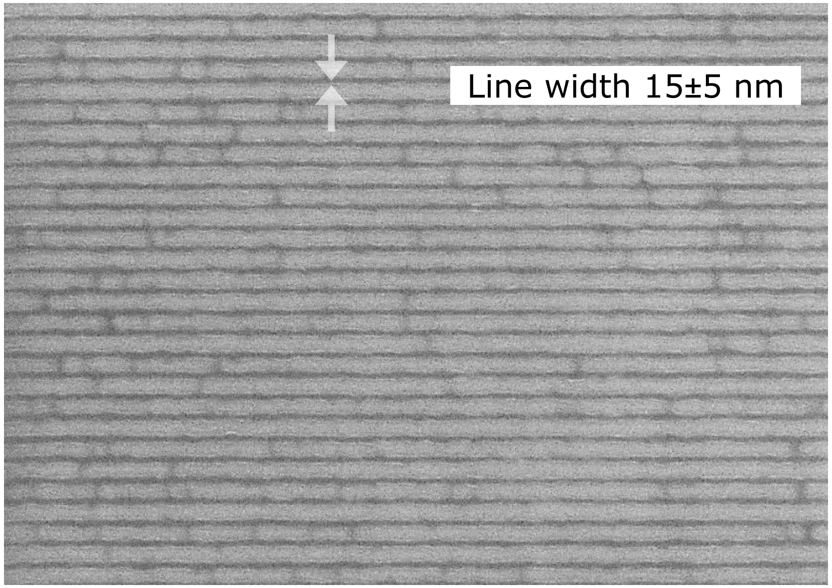
Lines and spaces pattern (half-pitch 100/50 nm)

Proximity printing
Half-pitch 100 nm, distance z ≈ 0 µm
Resist:ZEP520A



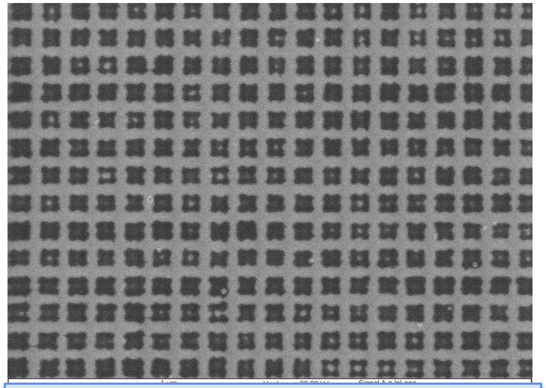
→ Same lithography mask
→ Pitch reduced by factor 2
→ Line width reduced by factor ~10

Achromatic Talbot Self-Image
Half-pitch 50 nm, distance z ≈ 50 µm
Resist:ZEP520A

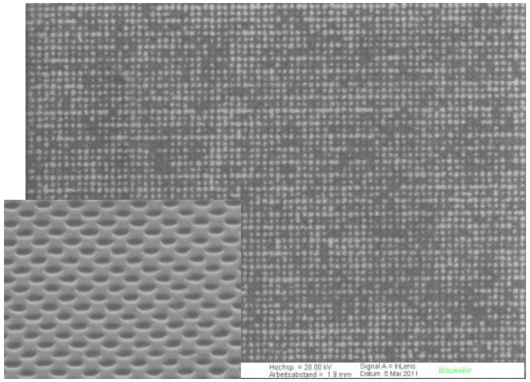


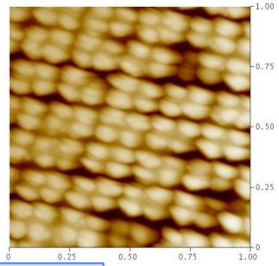
Exemplary application – cross-bar arrays for phase change memory (PCRAM)

Applications

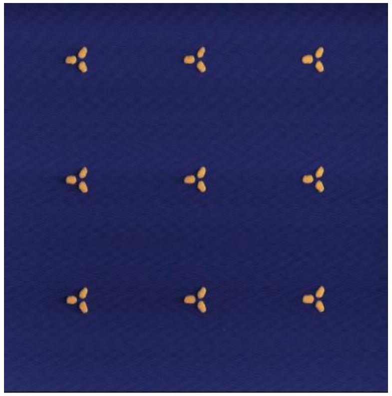


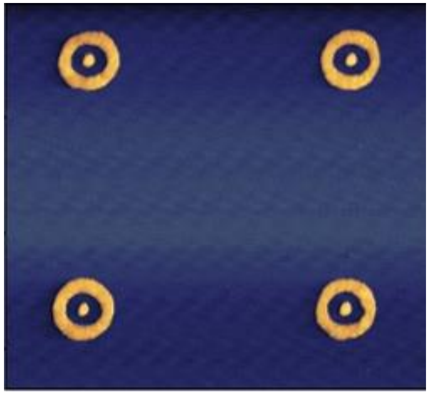
cross-bar arrays for PCRAM

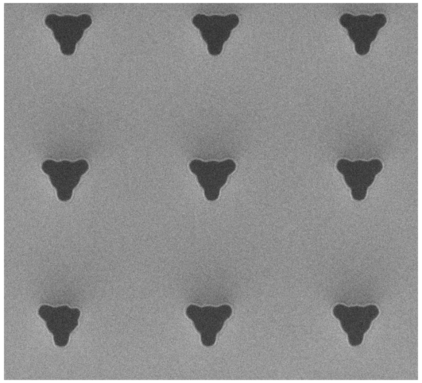




nanodot-arrays for QD self assembly

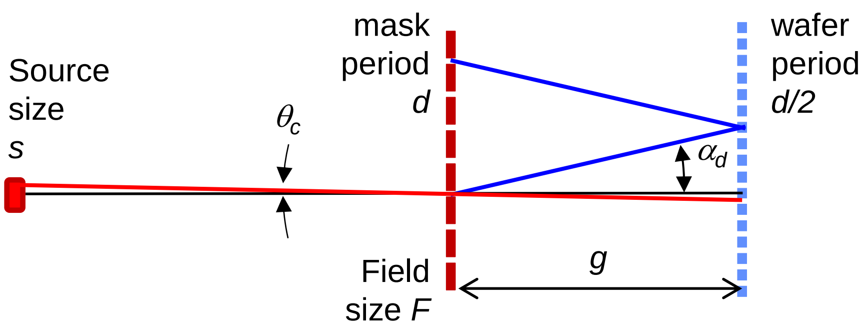






Nanophotonic resonators

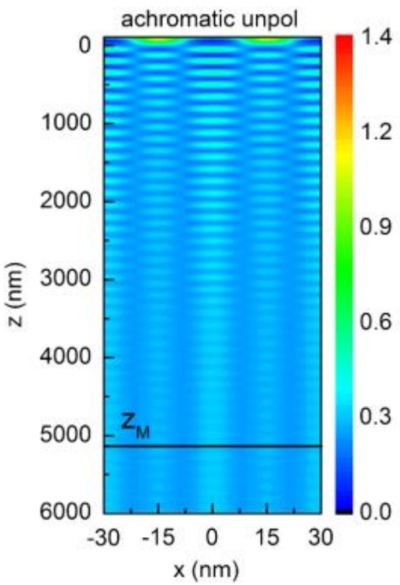
Radiance requirement for Talbot self-imaging lithography

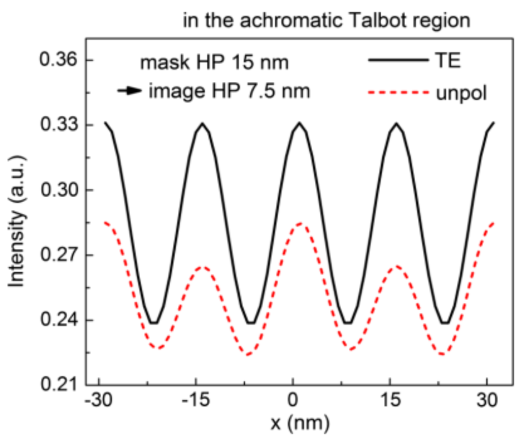


Mainly 0, 1st and -1st orders contribute to Talbot self-imaging effect ($\sin\alpha_d = \lambda/d$)

Coherence requirement depends on period d and mask to wafer distance g:

$$\boxed{\theta_c \le \frac{d}{2g}}$$





Achromatic Talbot pattern for 15-nm half-pitch grating and cross-sections at *g* = 6 µm.

Exposure dose is determined by resist sensitivity D and MTF from mask to wafer

$$\Rightarrow \quad L \cong \frac{D/MTF}{t_{exposure}\cdot T_{system}\cdot \Omega_{illumination}}$$

$$\text{2d-array:} \quad \cong \frac{4\cdot D\cdot g^2}{MTF\cdot t_{exp}\cdot d^2}$$

$$\text{1d-array:} \quad \cong \frac{4\cdot D\cdot g^2}{MTF\cdot t_{exp}\cdot d\cdot F}$$

implies slit-like source, alignment issue

Danylyuk, Kim, et.al., J. Micro/Nanolith. MEMS MOEMS 12 (3), 033002 (2013)

Summary – radiance requirements

EUV and soft x-ray microscopy enables imaging of nanometer sized object features with high analytical sensitivity, very good spatial resolution, and penetration depths compatible with relevant sample sizes.

Source radiance requirements are derived from the fundamental considerations of sample resolution, image contrast, detector quantum efficiency and throughput.

Photon counting is characterized by Poisson statistics. Requirement of being able to distinguish between (noisy) signal and (noisy) background results in inverse dependence of radiance on contrast squared.

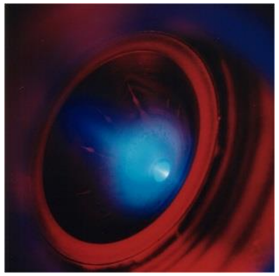
The etendue used by a high resolution EUV imaging application scales with the area of the smallest feature to be resolved or detected which is of the order of λ^2.

Taking into account conservation of etendue ("not compressibility" of light) and photon energy, the required radiance is proportional to λ^{-3}.

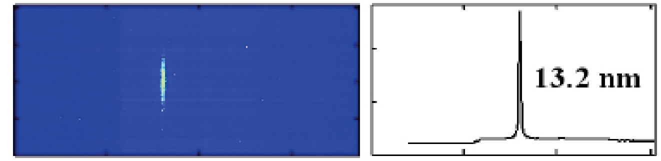
$$L_{source} = \frac{25 \cdot fps \cdot h \cdot c/\lambda}{C^2 \cdot T_{system} \cdot \pi \cdot NA^2_{illumination} \cdot A_{to\ resolve\ or\ detect}}$$

In accessing the nano-world with laboratory imaging systems, this strong dependence implies a serious challenge for the source development.

Outlook



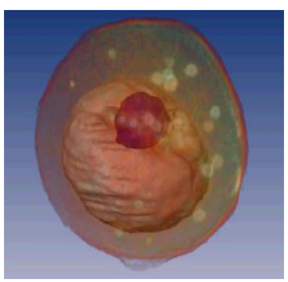
XUV plasma based sources
- new very efficient technology
- “Aachener Lampe” successfully used in EUVL & metrology



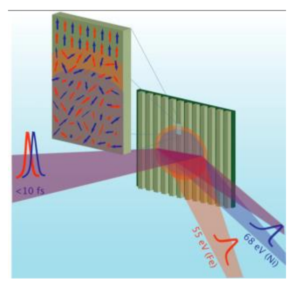
High brilliance metrology sources
- small emitting volume
- XUV lasers

future research challenges

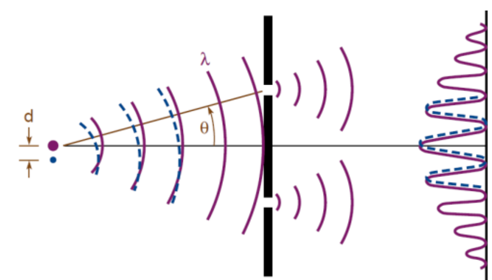
3d imaging
- combining of lateral and in-depth resolution
- cell nanotomography



Spectro-microscopy
- combining of spectral and lateral resolution
- magnetic domains



Coherence
- holography
- lens less imaging
- interference litho



Prof. Dr. Larissa Juschkin

2014 International workshop on EUV and soft x-ray sources
November 3-6, 2014, UCD, Dublin, Ireland

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Coherent Imaging Group

John Miao, Rui Xu …

Thank you very much for your attention!